Neutrino event generation and ArgoNeuT cross section measurement predictions with GENIE and Nuance

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Abstract

The GENIE[1] and Nuance[2] neutrino generator implementations for LAr and the ArgoNeuT experiment are described. Also, similarities and differences between the generators in terms of cross sections, intra-nuclear scattering, kinematics, and interaction parameters are discussed.

1 Introduction

Without a universal standard for event generation, the neutrino community is often forced to consult more than one neutrino generator for a given experiment. The Nuance and GENIE neutrino event generators are presented in this document for use with liquid argon and more specifically, the ArgoNeuT experiment. Among the world's generators, Nuance has been chosen due to collaboration overlap with its main user-collaboration, MiniBooNE, and GENIE has been chosen as it is fast becoming the aforementioned universal generator for all targets, energies, and neutrino species.

ArgoNeuT is an R&D-oriented experiment with physics measurement capability. This document serves as a fairly comprehensive overview of the physics possibilities in ArgoNeuT and as a pedestal for physics measurements in future liquid argon detectors. The corresponding code has passed all sanity checks and is actively being used to simulate neutrino interactions on liquid argon at BNB and NuMI energies.

2 Event generation

The Nuance (v3) and GENIE (v2.4.0) neutrino generators are both in the CVS ANT_G4 simulation at ANT_G4/ANT_Nuance and ANT_G4/ANT_GENIE, respectively[3]. READMEs are available in these directories. Along with ANT_G4, these pieces of code will be available in the Larsoft framework at /afs/fnal.gov soon.

[1] http://www.genie-mc.org

[2] http://nuint.ps.uci.edu/Nuance/

[3] ANT refers to ArgoNeuT.

Each generator takes the standard gnumi (v19) near detector ν_μ , $\overline{\nu}_\mu$, ν_e , $\overline{\nu}_e$ flux files (gnumiv19nearflux_le010z185i.hbook in Nuance and gnumiv19nearflux_le010z185i.root in GENIE) and produces events (neutrino direction +z) with a random spatial distribution in the ArgoNeuT TPC. The output primary particles can then be seamlessly read by Geant4 and tracked through the argon medium of the TPC. Example root macros are available for analyzing the output. Note that although the Nuance output is in a .hbook format by default, a "Nuance reader" has been written into ANT_G4. Both generators also come with utilities to produce cross section and rate plots. Also, a NuMI event driver utility, allowing the parent pion and proton-target kinematic information to be kept, is being written into GENIE and should be available soon.

3 Generator usage and modification

The READMEs mentioned above should be sufficient guidance for running Nuance and GENIE. To run the Nuance or GENIE output through Geant4, one needs to simply move (mv) the GENIE3.root or Nuance3.hbook file to ANT_G4/data and then choose what generator to use in ANT_G4/my.mac. Note that high statistics data files for both generators are already available in the ANT_G4/data directory and one need not run GENIE/Nuance to start simulating events in the detector with Geant4.

3.1 LAr-specific modifications to GENIE and Nuance

The GENIE software is billed as a "Universal Neutrino Generator" and has been treated as such. Apart from specifying argon-40 as the interaction medium at run time, nothing has been changed in GENIE with regard to neutrino interactions. Making an apple-to-apples comparison to Nuance did require some code additions, however. Constantinos Andreopoulos, the lead developer of GENIE, confirms that argon is simulated correctly in GENIE but should benefit from an upgraded nuclear model based on fully validated spectral functions. The model may be available in the next GENIE release (v2.6.0) in Fall 2008. Note that there is a single recent paper on argon spectral functions [1].

A study comparing GENIE/Nuance and the argon-dedicated neutrino generator GENEVE will take place in the near future. The GENIE documentation notes that "(GENIE) encompasses and supersedes a host of successful Fortran neutrino MC generators, such as GENEVE, NEUT, NeuGEN, and NUX that have been used extensively in the design and exploitation of many previous and current neutrino experiments"[2].

Nuance was originally created for neutrino interactions in a water Cherenkov detector. The MiniBooNE collaboration has edited the Nuance code extensively in order for it to simulate neutrino interactions on carbon (CH_2). Taking these code changes as a template, Alessandro Curioni and the author have edited Nuance to simulate neutrino interactions on (liquid) argon-40.

3.1.1 Nuance for LAr

One card file and five source files in Nuance have been edited. Changing the card file is sufficient for neutrino-argon interactions in Nuance for everything before final state interactions. The source files have been changed to simulate final state interactions in the argon nucleus.

`Nuance_defaults.cards` is the card file that specifies all the user-knobs and parameters in Nuance. The file has been edited to include N and Z, density, the neutron and proton Fermi momentum, and the nucleon binding energy of (liquid) argon-40.

`ninmat.f` is a messenger-type file. It was changed to look for an instance of 'argon' in the `Nuance_defaults.cards` file.

`prtnuc.inc` is a common block describing nuclear density and various hadron-nucleon cross sections. A nucleon energy cut, below which nucleons are not created in Nuance, has been reduced to 960 MeV, chosen to coincide with the estimated energy threshold for nucleon detection in a LArTPC.

`partnuc.inc` handles final-state interactions with a basic nuclear model that uses nuclear density and Fermi momentum, taking into account changes in nuclear density as nucleons leave the target nucleus [3]. The argon-specific nuclear density parameters and Fermi momentum distribution model have been added.

`rgeneralnuc.f` describes the differential nuclear matter density of a given nucleus at given radius. The Woods-Saxon parameters for argon-40 have been added.

`rodist.f` handles the ρ_0 parameter in the Woods-Saxon model. A (=40 in argon-40) goes into the ρ_0 calculation.

4 Rates

The following ArgoNeuT rates are taken from Nuance and utilize Nuance's definition of DIS and resonant interaction of W<1.7 GeV [4].

[4] See future sections for more information.

	Nuance channel	Reaction	#/180 days (1.44E20 POT)
	n/a	ν_μ CC	26578
	n/a	$\overline{\nu}_\mu$ CC	2218
	n/a	ν_e CC	540
	n/a	ν_e CCQE	52
CCQE	1 (CC)	$\nu_\mu n \longrightarrow \mu^- p$	4376
NCelastic	2 (NC)	$\nu_\mu n \longrightarrow \nu_\mu n$	794
	2 (NC)	$\nu_\mu p \longrightarrow \nu_\mu p$	543
Single pion resonant	3 (CC)	$\nu_\mu p \longrightarrow \mu^- p \pi^+$	3148
	4 (CC)	$\nu_\mu n \longrightarrow \mu^- p \pi^0$	1859
	5 (CC)	$\nu_\mu n \longrightarrow \mu^- n \pi^+$	2421
	6 (NC)	$\nu_\mu p \longrightarrow \nu_\mu p \pi^0$	630
	7 (NC)	$\nu_\mu p \longrightarrow \nu_\mu n \pi^+$	528
	8 (NC)	$\nu_\mu n \longrightarrow \nu_\mu n \pi^0$	793
	9 (NC)	$\nu_\mu n \longrightarrow \nu_\mu p \pi^-$	704
DIS	91 (CC)	$\nu_\mu N \longrightarrow \mu^- X$	11598
	92 (NC)	$\nu_\mu N \longrightarrow \nu_\mu X$	3739
Coherent/diffractive	96 (NC)	$\nu_\mu A \longrightarrow \nu_\mu A \pi^0$	275
	97 (CC)	$\nu_\mu A \longrightarrow \mu^- A \pi^+$	513

The reaction products shown above are not necessarily final-state particles as they have not yet escaped the nucleus and thus, have not yet been subject to intra-nuclear interactions.

5 Cross sections

ArgoNeuT may only be able to make one cross section measurement (CCQE). However, two of ArgoNeuT's main goals are to study software for future LAr experiments and to demonstrate the event ID power of LArTPCs. Even with the help of a downstream detector (the MINOS near detector or MINERvA), ArgoNeuT will have a difficult time fully reconstructing single pion resonant and coherent events. However, demonstrating the ability to tag these events with unprecedented efficiency using dE/dx and topology near the event vertex is of great interest to the neutrino community and vital for future experiments. Therefore, all relevant processes at NuMI energies are discussed in this note.

Neutral current elastic, single pion resonant, and coherent events will be very important to the MicroBooNE experiment. These cross sections are interesting in and of themselves and not only as a background for signal processes. It is also important to consider DIS processes for ArgoNeuT, future long baseline neutrino oscillation experiments, AND MicroBooNE as MicroBooNE will see $\sim$30000 events from the off-axis NuMI beam with 4% of those DIS [4].

All of the generator cross section information that follows is a non-comprehensive summary of what can be found in the Nuance and extended GENIE (and INTRANUKE [5]) documentation.

5.1 CCQE ($\nu_\mu n \rightarrow \mu^- p$)

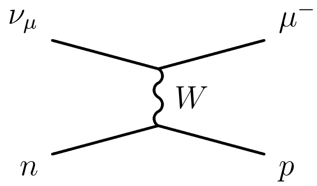

Figure 1: A CCQE interaction.

With only an outgoing muon and proton, a CCQE event is perhaps the easiest neutrino interaction to identify and reconstruct. Also, the cross section is comparatively high at BNB/NuMI neutrino energies. A CCQE cross section measurement in ArgoNeuT (and possibly an M_A measurement) seems likely with ∼4400events/180 days, 54% proton containment [6], downstream MINOS/MINERvA muon containment (Figure 2 shows the CCQE muon angle for events in ArgoNeuT), and high event-ID efficiency. Note that in 47% of CCQE events, the proton is contained and the muon enters the MINOS ND [6]. GENIE handles CCQE interactions with an implementation of Llewellyn-Smith[7] and Nuance uses Smith and Moniz [8]. Both generators use the Fermi gas model for Pauli blocking. The free nucleon cross section for a given M_A value is well known, so any disagreement between the generators would largely come from different nuclear suppression factors (a function of Q^2) in the Fermi gas model. Note that the CCQE cross section is nearly linearly dependent on M_A and the default value of M_A=.990 GeV used in GENIE and Nuance is low compared to the recent measurements of K2K[9] and MiniBooNE[10]. However, M_A can only be considered in the context of a form factor model as different models need different M_A values in order to get the same agreement with data. M_A and other parameters (see 'Parameters' section) can be changed easily in both generators. By default Nuance uses the Bosted [11] quasi-elastic vector form-factor model and GENIE the BBA2005[12] model. Both generators allow other form-factor models to be used.

5.2 Neutral current elastic ($\nu_\mu N \rightarrow \nu_\mu N$)

The neutral current elastic proton channel is especially attractive due to the ∼50% probability of proton containment in the ArgoNeuT active volume. Also, tagging (but not reconstructing) neutron events may be possible if more than one track due to a neutron interaction is seen in the TPC. A detailed study of this process should occur in the near future. The neutral current proton to CCQE ratio ($\frac{\nu_\mu p \rightarrow \nu_\mu p}{\nu_\mu n \rightarrow \mu^- p}$) may also allow a Δ_s measurement using ArgoNeuT. This measurement will benefit greatly from ArgoNeuT's high event ID tagging efficiency utilizing dE/dx, topology, and the ability to distinguish protons from neutrons (if the neutron-tagging requirement is met). Disagreement between the generators may be due to the fact that few measurements are available (of $\frac{d\sigma}{dQ^2}$ [5]). However, [13] is the main resource for this channel and both generators seem to use this paper for the measurement and cross section modeling at some level.

[5]For neutral current elastic interactions, $Q^2 = 2m_n KE$

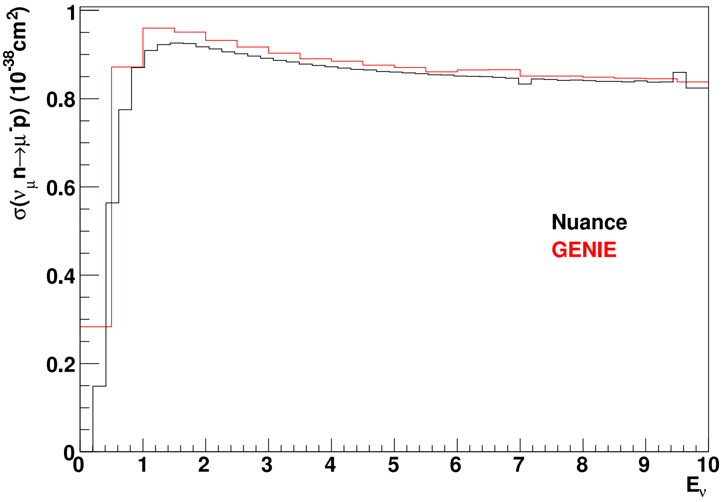

Figure 2: CCQE cross section on LAr (M_A=.990 GeV) in Nuance and GENIE.

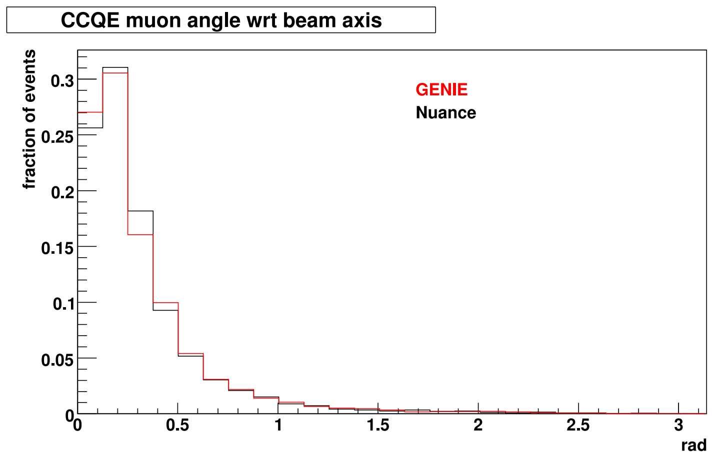

Figure 3: CCQE muon angle with respect to the beam axis in ArgoNeuT.

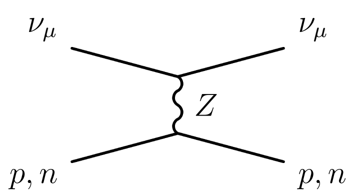

Figure 4: A NCelastic interaction.

5.3 Single pion resonant ($\nu_\mu N \rightarrow lN^{(')}\pi$)

Although fully reconstructing a single pion resonant event will prove to be a challenge with ArgoNeuT, a cross section measurement of a high rate channel like CCpi+ may be possible. Furthermore, demonstrating the event-ID power of an LArTPC in CCpi+ and other resonant channels is

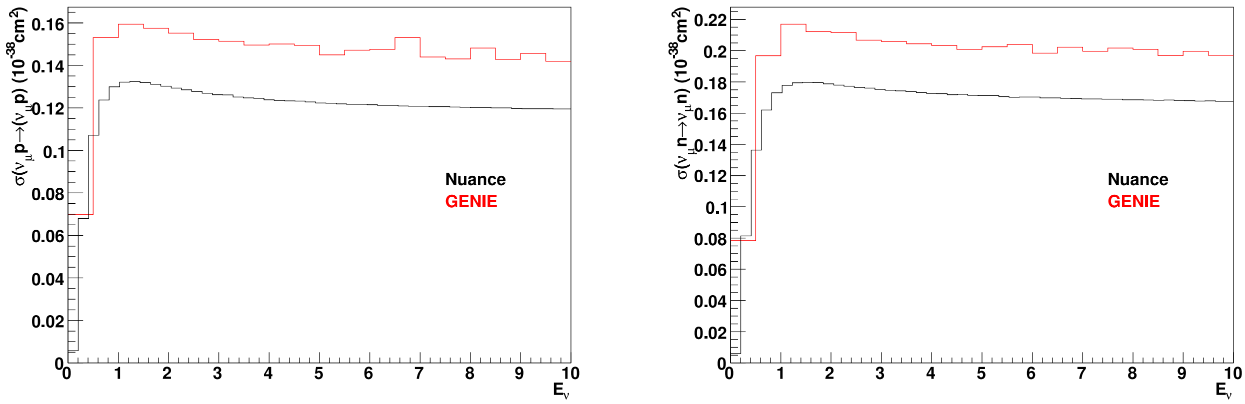

Figure 5: Proton (left) and neutron (right) NCelastic cross section on LAr in Nuance and GENIE.

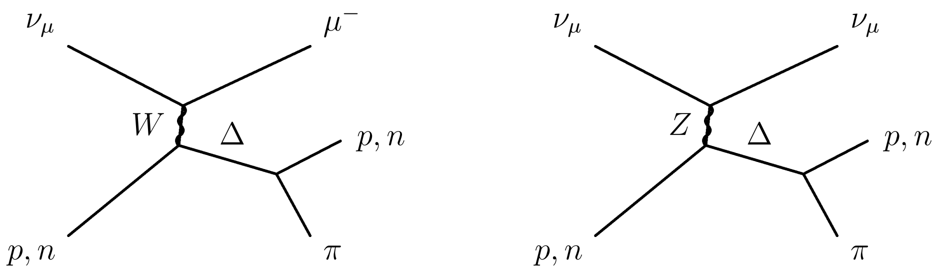

Figure 6: Single pion resonant interactions (CC on left, NC on right).

important. GENIE and Nuance use Rein-Sehgal [14] for NC and CC resonance interactions. GENIE neglects interference between resonances with equal isospin while Nuance's single pion channels interfere coherently (with the other channels interfering incoherently). The axial vector mass, essentially the main parameter in the Rein-Sehgal model, has been made the same in Nuance and GENIE (see the "Parameters" section). However, the generators define non-resonant background in different ways as discussed in "The transition region" section. Aside from small width and mass differences, the implementation of Rein-Sehgal is also slightly different due to the fact that Nuance uses 18 resonances while GENIE counts 16 resonances "that are listed as unambiguous at the latest PDG baryon tables"[2].

Note that the single pion cross section plots that follow show resonant+non-resonant=total cross section and have been made after altering GENIE's DIS definition to relatively coincide with Nuance's by requiring that to be considered DIS, the invariant mass W must be greater than 1.7 GeV[6]. A DIS event in GENIE with W<1.7 GeV is considered "non-resonant" background in the single pion resonant cross section plots below and is added onto the resonant part to give the total cross section for a given channel.

As GENIE handles such events differently than Nuance it is worth explicitly stating what goes into a particular channel. As an example we arbitrarily consider channel #4 ($\nu_\mu n \rightarrow \mu^- p \pi^0$) in GENIE. The resonant part requires an incoming muon neutrino interacting with a neutron

[6] GENIE's integrity remains as the cuts were made after event generation and do not affect the source code.

via charged-current, W-selected less than 1.7 GeV, resonance creation, one primary (before intra-nuclear scattering) proton, zero primary neutrons, one primary π^0, zero primary π^+s, and zero primary π^-s. The non-resonant part includes events originally defined as charged-current DIS events with an incoming muon neutrino interacting with a neutron via charged current, W-selected less than 1.7 GeV, one primary proton, zero primary neutrons, one primary π^0, zero primary π^+s, and zero primary π^-s.

The transition region ambiguities (discussed below) aside, the correct way to place a non-resonant event in a particular channel is unclear. The primary state should obviously include a π^0. But, should the cut exclude events with more than one primary π^0? Should the cut exclude events with π^+ and/or π^-? Should the cut require a final state π^0 and what about pion re-absorption?

In summary, the concept of "channel" is ambiguous in two different ways:

1. There are three different processes (resonant, normal DIS, transition DIS) that can contribute to the same hadronic system before intra-nuclear scattering.

2. Intra-nuclear scattering affects the final-state topology of an event. For example, a topology with $X\pi^0$ in the final state may have come from a $Y\pi^-$ initial hadronic system with the π^- undergoing a charge exchange process ($\pi^- Y \rightarrow \pi^0 X$).

Luckily, GENIE's channel scheme is not set in stone and the above questions can be answered in different ways by the user.

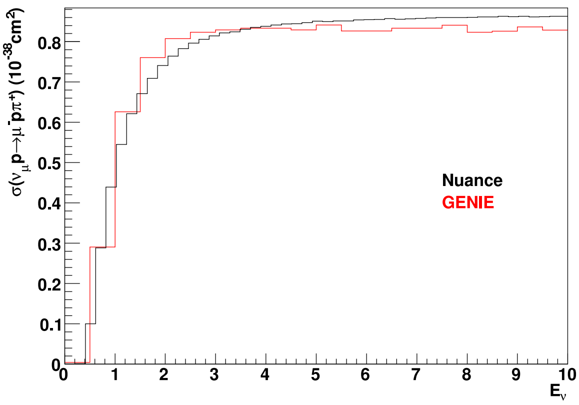

Figure 7: Single pion resonant CCpi+ cross section on LAr in Nuance and GENIE.

5.4 Deep Inelastic Scattering ($\nu_\mu N \rightarrow lX$)

Deep inelastic cross sections are computed using the modified leading order QCD Bodek-Yang (BY) model ([15] in Nuance and [16] in GENIE). However, GENIE includes nuclear effects (shadowing, anti-shadowing) and longitudinal structure functions (with the Whitlow R parametrization [17]) while Nuance does not. The DIS cross section plots below use a consistent definition of DIS (requiring W>1.7 GeV) discussed in the "Single pion resonant" section. GENIE and Nuance both use

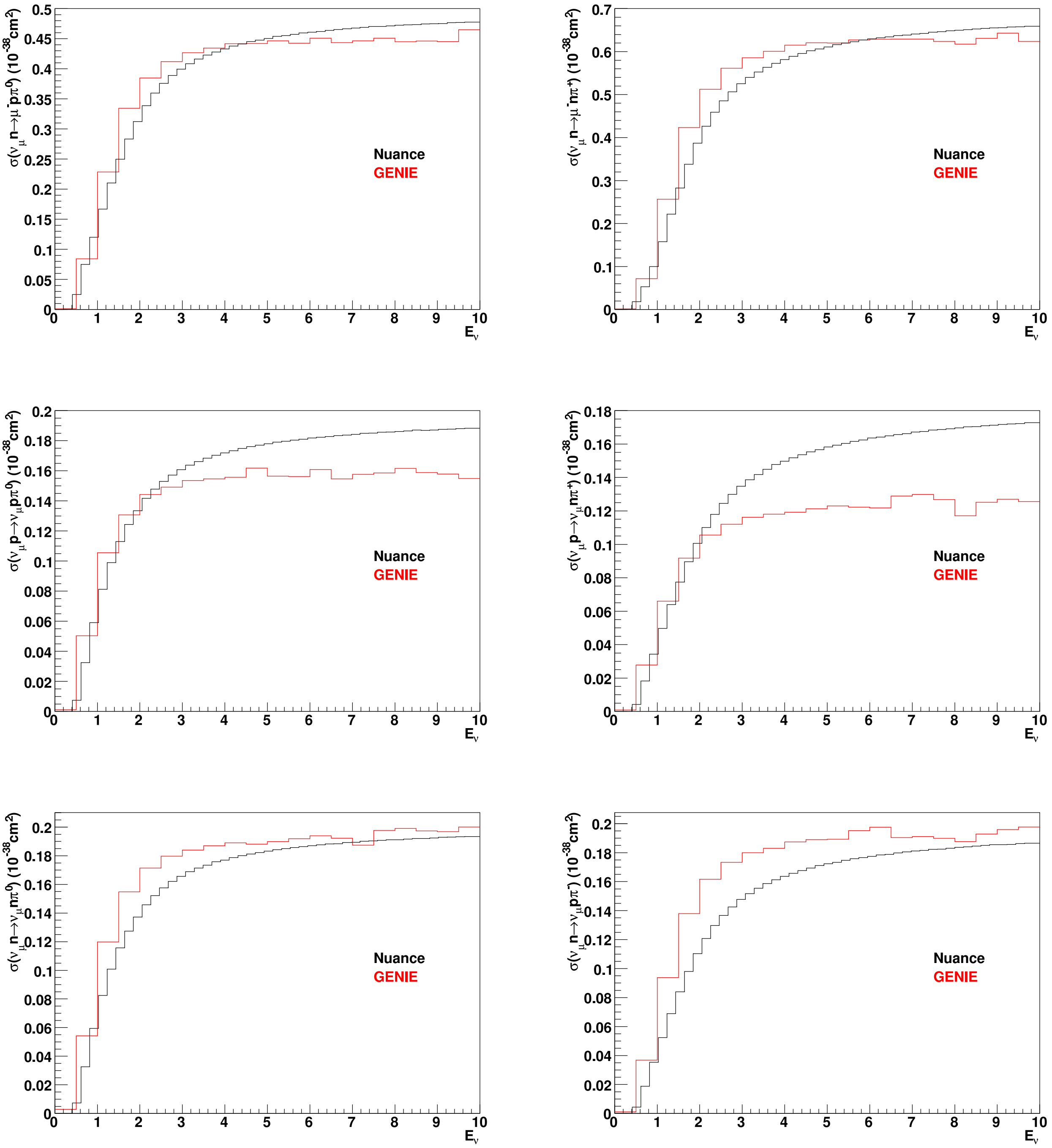

Figure 8: Single pion resonant cross sections on LAr in Nuance and GENIE.

a combination of a KNO-based model and a tuned[7] LUND-based model [19] [20] for hadronization and hadron multiplicity. The Nuance documentation notes that "deep-inelastic scattering is undoubtedly the regime where nuance currently lags behind the state-of-the-art in other generators

[7]The model was tuned at the NOMAD experiment, in the context of the NUX generator [18].

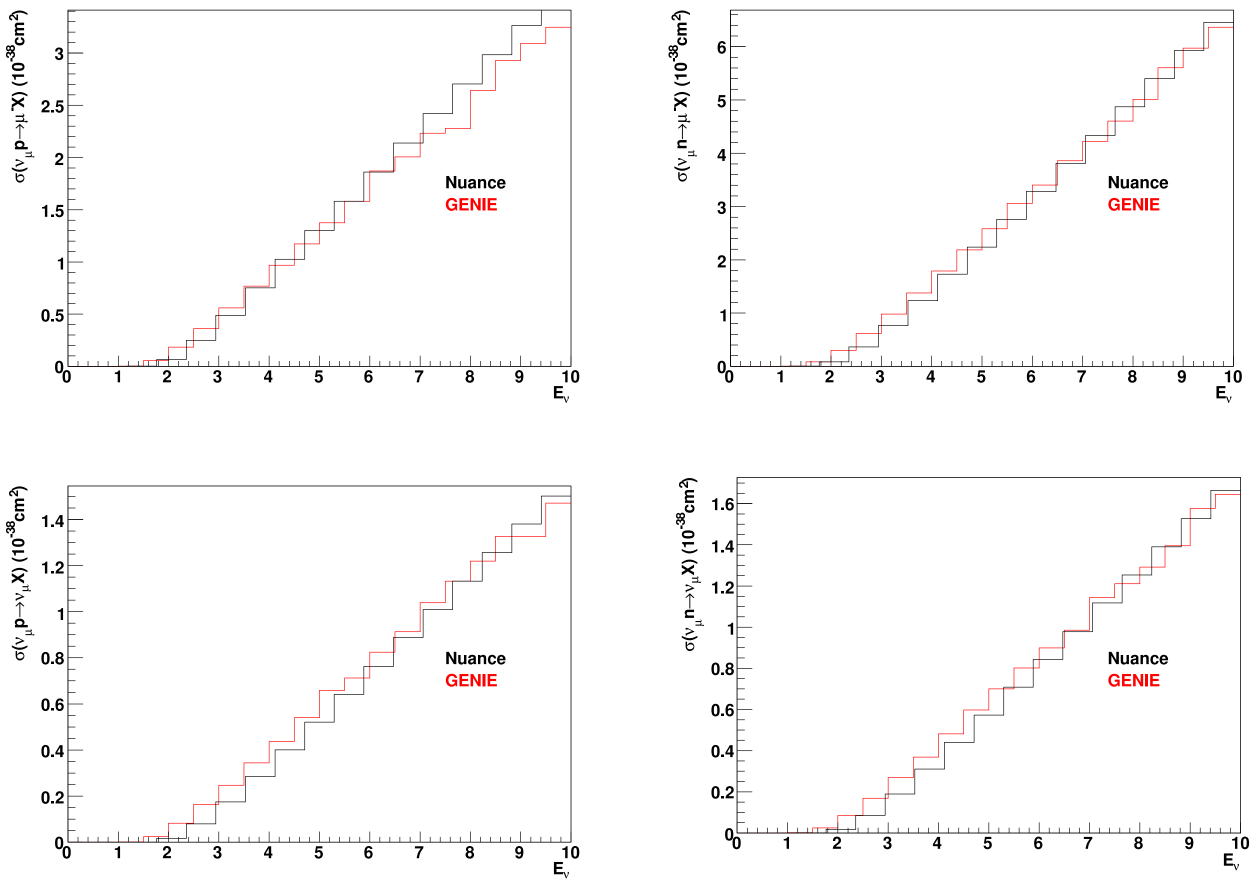

Figure 9: DIS cross sections on LAr in Nuance and GENIE.

dedicated to high-energy neutrino physics"[21].

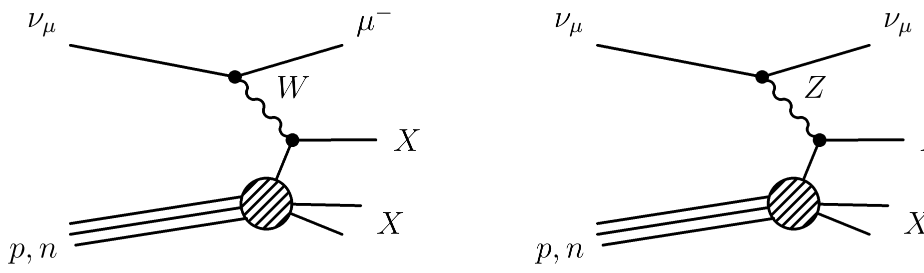

Figure 10: DIS interactions (CC on left, NC on right).

5.5 Coherent ($\nu_\mu A \rightarrow l A \pi^{+,0}$)

The coherent neutrino interaction, where a neutrino scatters from the whole of the nucleus, is perhaps the least well understood channel for 1-10 GeV scale neutrino energies. Although both channels can contribute a >10% increase to total neutrino-induced pion production, the neutral current mode is especially important for long baseline neutrino oscillation experiments as it is a background for the signal ν_e process. Nuance and GENIE both use the Rein and Sehgal cross section calculation[22]. However, GENIE uses the updated Rein version [23] with the modified PCAC formula, including destructive interference between some terms for CC interactions. There is more than 100% uncertainty on the cross section for the NC coherent π^0 channel at relevant energies and there is no existing data below 2 GeV. Also, pion absorption in coherent interaction is poorly understood and can lead to a factor of two difference in coherent rate [24]. MiniBooNE has recently published a coherent π^0 to single π^0 resonant fraction of $(19.5 \pm 2.7)\%$ at $<E_\nu>\approx 1.1$ GeV, 35% lower than the Rein-Sehgal prediction [25] [26]. The K2K collaboration show data consistent with no CC coherent π^+ production at $<E_\nu>\approx 1.3$ GeV [27]. Similar behavior is seen from preliminary results at SciBooNE [28]. These results are inconsistent with the original Rein-Sehgal paper as the model (while assuming $\sigma \sim A^{\frac{1}{3}}$ in order to compare different targets) predicts $\sigma(CC)=2\sigma(NC)$. However, the updated Rein paper predicts a suppression of coherent π^+ production in the $Q^2<0.1$ GeV^2 region of a factor of $\approx .77$ [23]. Other coherent production models are difficult to test and do not provide pion kinematics [27]. The upcoming MiniBooNE CCpi+ measurement should shed some light on the problem. Also, the MINERvA experiment [29] is poised to measure 85000 CC coherent π^+ and 37000 NC coherent π^0 on different targets (He, C, Fe, Pb) in the NuMI beam starting in 2009[26]. Measuring the dependence of the coherent cross section on atomic number is a priority for the experiment.

Figures 13 and 14 show the Q^2 (left) and π^+ angle (with respect to the beam axis) distributions in single pion resonant and coherent events. The coherent event signature, a forward-scattered pion, may be difficult to discern with low statistics in ArgoNeuT (513 CC events and 275 NC events in 180 days[8]) and low event containment. However, ArgoNeuT will benefit from being able to throw out those single pion events with a clear proton or neutron track indicative of a resonant event.

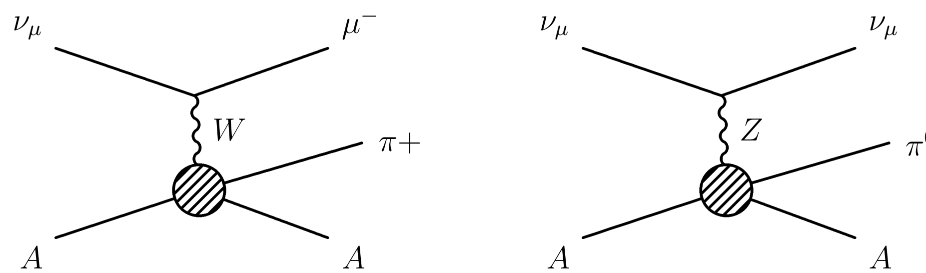

Figure 11: Coherent interactions (CC on left, NC on right).

6 Kinematics

The Nuance and GENIE generators largely agree on cross section functions considering that precise cross section data from 10 MeV to 10 GeV is usually lacking and a 20% "disagreement" in a particular channel is often not unexpected. Furthermore, models like Rein-Sehgal (resonant, single

[8]Note that the cross section is poorly known and these rates (from Nuance) cannot be taken seriously.

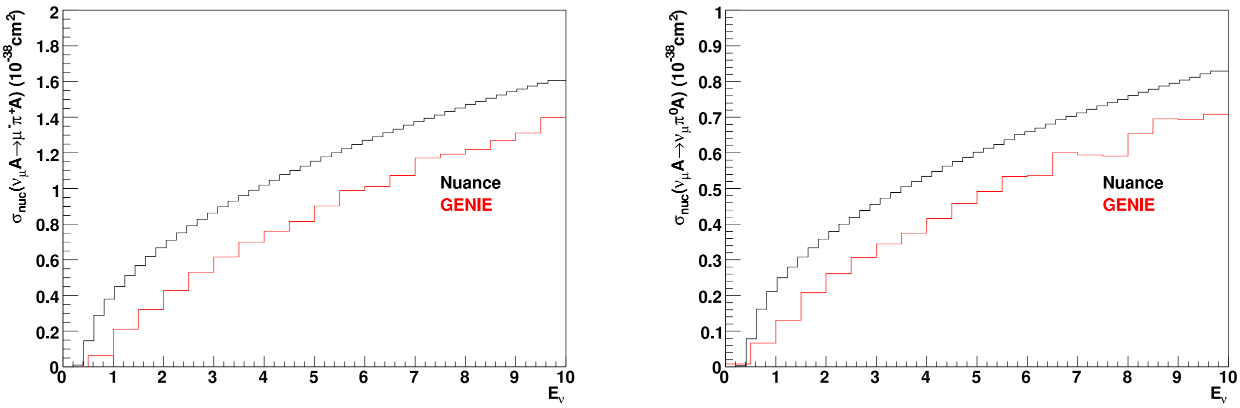

Figure 12: Charged current coherent π^+ (left) and neutral current coherent π^0 (right) cross section on argon-40 in Nuance and GENIE.

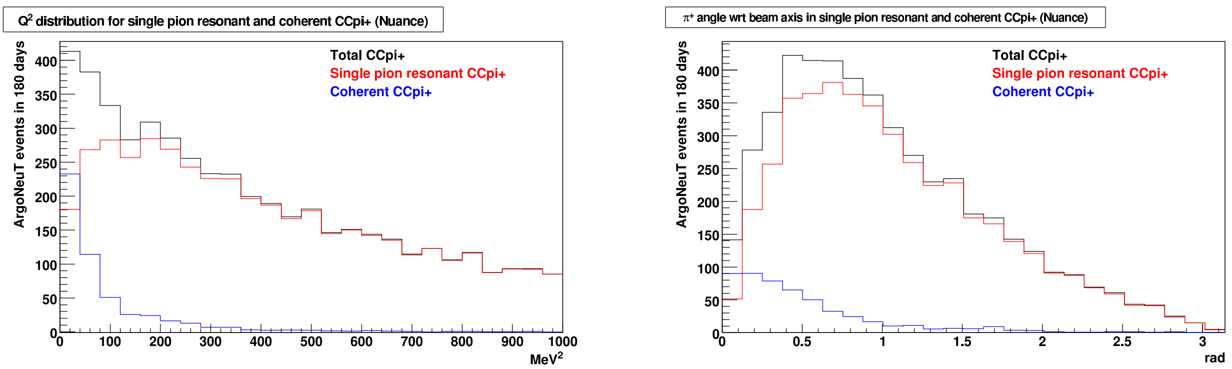

Figure 13: Single pion resonant inclusive ($\nu_\mu p \longrightarrow \mu^- p \pi^+$ and $\nu_\mu n \longrightarrow \mu^- n \pi^+$) and coherent CCpi+ Q^2 (left) and π^+ angle with respect to the beam axis (right) in Nuance. Notice the low-Q^2 and π^+ forward scattering for coherent CCpi+.

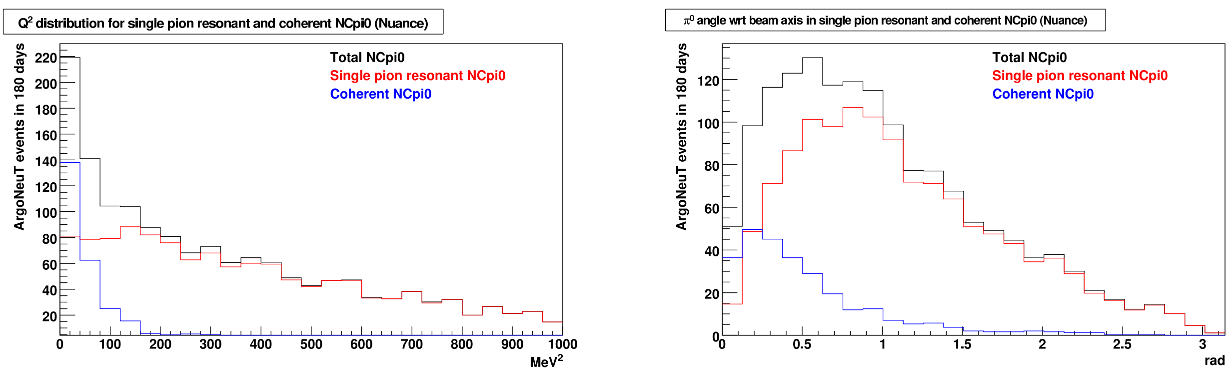

Figure 14: Single pion resonant inclusive ($\nu_\mu p \longrightarrow \nu_\mu p \pi^0$ and $\nu_\mu n \longrightarrow \nu_\mu n \pi^0$) and coherent NCpi0 Q^2 (left) and π^0 angle with respect to the beam axis (right) in Nuance. Notice the low-Q^2 and π^0 forward scattering for coherent NCpi0.

pion), and Bodek-Yang (DIS) are universally accepted for neutrino cross sections. Nuclear effects like Pauli blocking and Fermi momentum can alter the functions [along with different (and non-trivial) model implementation] but the free-nucleon cross sections should be fairly similar between generators.

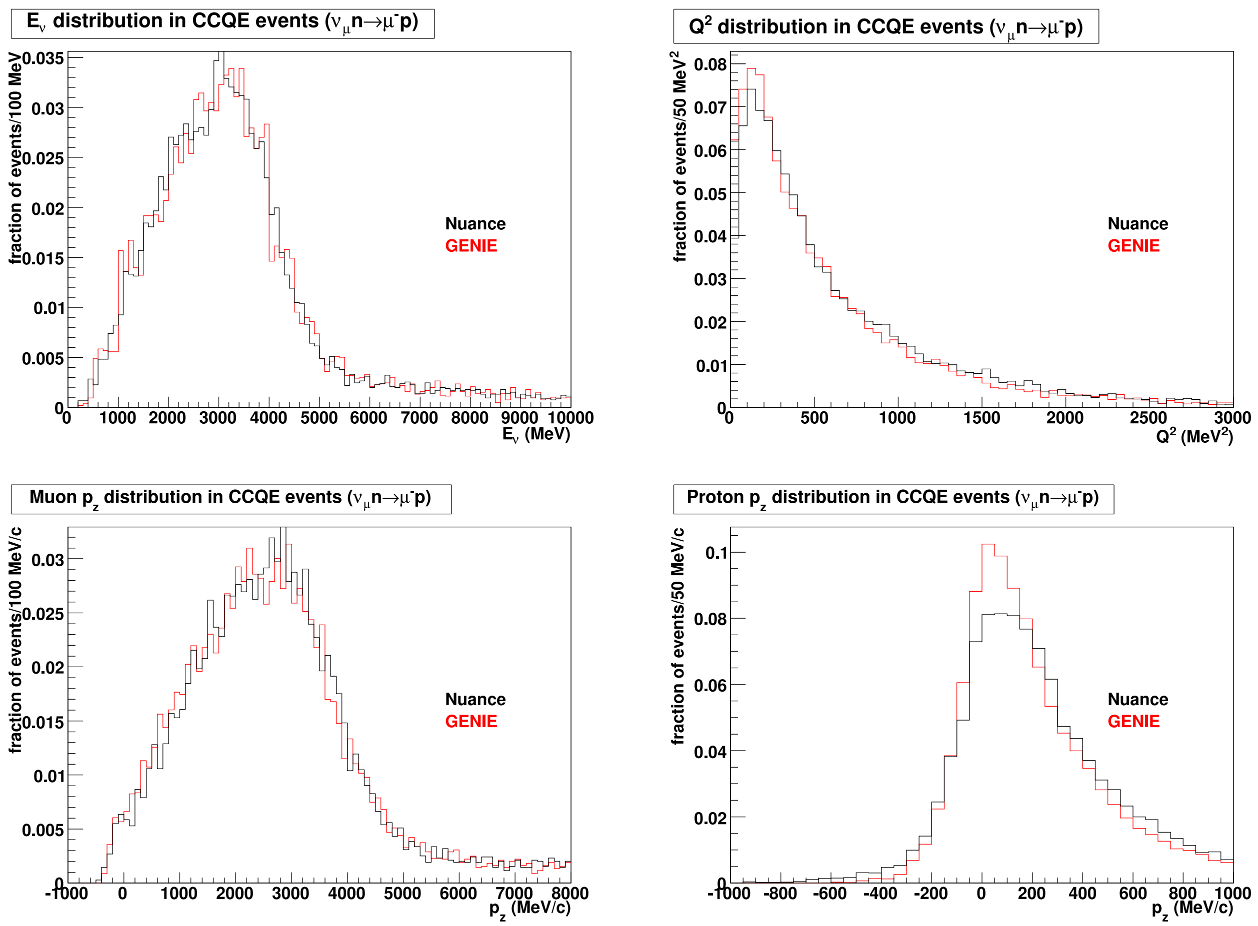

Figure 15: CCQE kinematics in ArgoNeuT.

Particle multiplicity and kinematics, largely based on the final-state-interaction model being used, are what really separate one generator from another. As final-state-interactions are not observable and observable processes do not necessarily correspond to their theoretically conjectured unobservable past, we can expect that there will be some disagreement between models. Without mentioning the cross section of such interactions, modeling the energy and angular distribution of the products of intra-nuclear collisions is difficult as there are many types of interactions and correspondingly few data points. The kinematics of intra-nuclear pion absorption is an interesting example. An absorbed pion can drastically affect the reconstructed neutrino energy as the pion's energy is often distributed to a large number (>2) of nucleons [30][31]. These nucleons may have kinetic energy below that which is detectable and therefore lead to a reconstructed neutrino energy that is too low. In Nuance, an absorbed pion's energy gets distributed in a 2-nucleon final state ($\pi N \rightarrow NN$) [32]. GENIE's INTRANUKE goes a step further and distributes the pion's energy

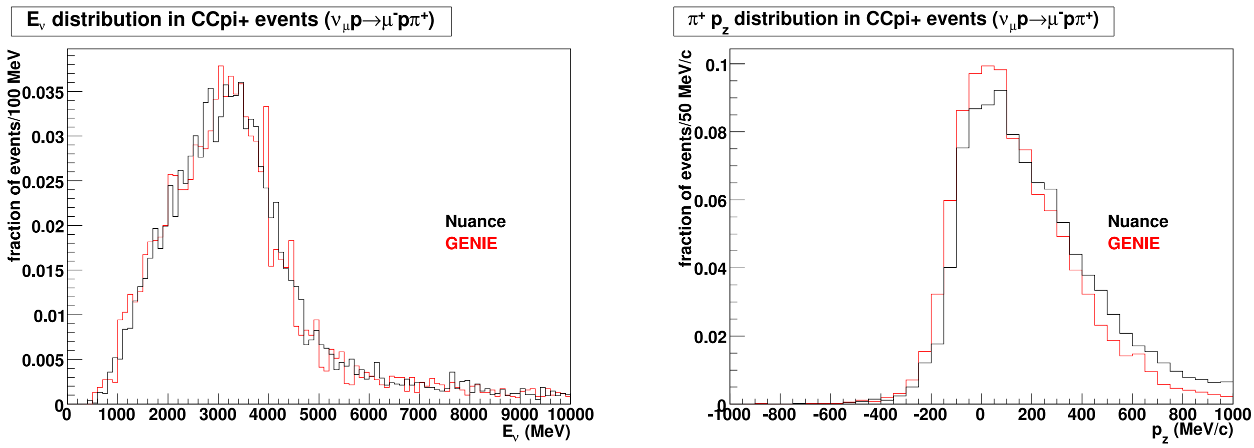

Figure 16: CCpi+ kinematics in ArgoNeuT.

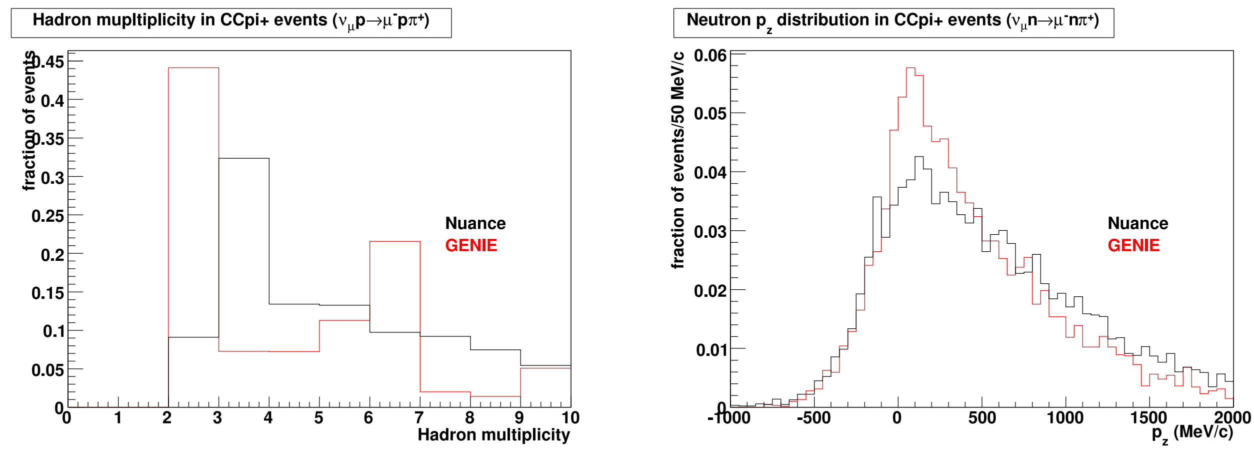

Figure 17: CCpi+ hadron multiplicity (left) and neutron kinematics (right) in ArgoNeuT.

according to phase space in one of the following channels: $\pi N \to np$, $\pi N \to pp$, $\pi N \to npp$, $\pi N \to nnp$, $\pi N \to nnpp$, and $\pi N \to n\pi^+\pi^0$.

Much work has been done in Nuance and GENIE to match the meson-nucleon/nucleus and nucleon-nucleon/nucleus cross section and angular distribution models to data. One can compare the generator results against data by running the simulation in reverse by starting a pion, kaon, or nucleon and impinging it on the outside of a nucleus. Data is available for O-16, C-12, Fe-56 and others. A study comparing Nuance to GENIE in this regard has not been completed by the author, although it is possible to perform such a study with both generators. Furthermore, a full study on a LArTPC's sensitivity to final state interactions has not been completed. A sense of the effects of different intra-nuclear models can be gathered from the kinematics plots shown here. Notice that although the neutrino energy and muon p_z distributions are quite similar between the generators, the final-state-hadron multiplicity and p_z distributions can differ significantly.

It is worth briefly summarizing the different approaches to the complicated process of intra-nuclear scattering here.

6.1 Nuclear processes in Nuance

In Nuance, a neutrino-nucleon interaction is given a starting position based on the Woods-Saxon nuclear density distribution $\rho(r) = \frac{\rho_0}{1+e^{(r-c)/z1}}$. The time it takes for a quark to hadronize in a "formation zone", during which the quark interacts with very low probability, is taken into account. The hadron formation time is 2.0 fm/c in Nuance. After creation, the hadron is then tracked through the nucleus in 0.3 fm steps after being given a 1.0 fm "free" (of interactions) first step. The hadron is stepped through the nucleus until it interacts with a nucleon or leaves the nucleus. The interaction probability is taken from pion-nucleon and nucleon-nucleon cross sections and angular distributions. A free step is given after every interaction. After an interaction, the hadron continues to step though the nucleus. Any interaction products follow the same stepping procedure. The nucleus is considered as an isoscalar sphere of effective radius $R = R_0 A^{1/3}$ (with $R_0 = 1.01$fm) with nuclear density and Fermi momentum radially dependent. Note that the differential nuclear density's affect on cross section is simulated. That is, Nuance takes into account the changing nuclear density as nucleons are pushed out of the nucleus. The pion-nucleon and nucleon-nucleon cross sections and angular distributions are based on HERA data[33] and have been tuned using the reversed-simulation method mentioned above with oxygen-16. Any data-less interaction cross section is treated with respect to isospin symmetry. Pion/nucleon absorption (e.g. $\pi N \to NN$), pion charge exchange (e.g. $\pi^+ X \to \pi^0 Y$), pion production (e.g. $\pi X \to \pi\pi Y$), inelastic and elastic scattering (e.g. $hX \to hY$ and $hX \to hX$), and nuclear de-excitation are simulated in Nuance. Further details can be found in the Nuance documentation.

6.2 Nuclear processes in GENIE

GENIE uses a C++ adaptation of NeuGEN's [34] updated INTRANUKE package for intra-nuclear hadron transport. A formation zone is also treated in GENIE with the SKAT model [35] which has formation time (of .52 fm/c) as the only free parameter. The incident neutrino is made to interact on the outside of the nucleus with interaction probability based on a modified Woods-Saxon model of the density distribution. The hadron scatters according to the hadron-nucleon cross section and the matter density at radius r giving a mean free path $\lambda = \frac{1}{\rho(r)\ \sigma_{hN}(E)}$ that is calculated as the hadron moves through the nucleus of radius $R = R_0 A^{1/3}$ (with $R_0 = 1.4$fm). The hadrons that are directly produced by the incoming neutrino are allowed to re-interact in the nucleus only once. After an interaction, the resultant particles are placed outside the nucleus and considered "final-state". Inelastic processes like pion absorption and inelastic scattering are well matched to data in this semi-classical model. However, the model ignores quantum mechanical wave-effects which are important for hadron-nucleus elastic scattering [5]. A modification to the c parameter in $\rho(r)$ fixes this to increase the nuclear size and thereby increase the model's hadron-nucleus cross section to fit data (π^+ on C-12 and Fe-56). This modification to $\rho(r)$ is only valid for hadron re-scattering in the nucleus and not for the initial neutrino-nucleus vertex. The hadron-nucleus cross sections in GENIE come from a complicated mash-up of the world's data [36][37][38][39][40][41][42][43][44] and the CEM03 calculations [45][46] for pion and nucleon interactions on Fe (with re-weighting for other nuclei). Pion/nucleon absorption, pion charge exchange, pion production, inelastic and elastic scattering, nuclear breakup, and nuclear de-excitation are simulated in INTRANUKE until $r = 3R$. Note that the probabilities for each channel do not come from hadron-nucleon cross sections. Instead, they come from existing hadron-nucleus data making the current version of INTRANUKE a simplified intra-nuclear cascade model. It should be emphasized that this is not a bad thing as 1) the simplified hadron-nucleus model is well matched to data, 2) there isn't data available for all possible hadron-nucleon cross sections and kinematics and 3) it is simple enough as to easily study systematics. Steve Dytman is currently working on an updated full cascade model which derives all interaction probabilities from hadron-nucleon cross sections. The hadron-nucleon INTRANUKE model will be fully validated and available in GENIE in Fall 2008. Further details can be found in the GENIE and INTRANUKE documentation.

7 The transition region

Nuance employs a convenient neutrino channel numbering scheme in order to differentiate one type of event from another. For example, CCQE events ($\nu_\mu n \rightarrow \mu^- p$) are given channel number 1, CCpi+ events ($\nu_\mu p \rightarrow \mu^- p \pi^+$) are channel number 3, NCDIS events ($\nu_\mu N \rightarrow \nu_\mu X$) are channel number 91, etc[9]. This scheme works well for an experiment like MiniBooNE with $E_\nu \sim$1 GeV. Problems arise, however, if the neutrino energy is higher than the DIS threshold and the transition region comes into play. Resonant and inelastic, non-resonant events can give similar final state particles in this region. In reality, the transition between scattering off of nucleons and scattering off of quarks is a smooth one and there is no hard cutoff between resonant and DIS interactions [21]. Assigning an event to a particular channel can become ambiguous in this region and beyond. Making an apples-to-apples comparison between generators on a channel-by-channel basis is complicated by the fact that there is no single standard for parametrizing the transition region and defining DIS.

The transition region and definition of DIS are nominally different between the generators. By default, Nuance cuts off resonant interactions above 1.7 GeV and parametrizes the turn-on of DIS in the following way:

$\sigma_{DIS} = \sigma_{BY} * F(W)$ $\qquad W_{high}$(= 1.7 GeV by default)

$F(W) = 0$ if $W < W_{high}$

$F(W) = .38 * \frac{(W - W_{high})}{2GeV - W_{high}}$ if $W_{high} < W < 2$ GeV

$F(W) = 1.0$ if $W > 2$ GeV

A non-resonant event producing a μ^-, π^+, and proton (with possibly more nuclear fragments) in the 1.7<W<2.0 GeV range will fall with some non-zero probability into channel 3 and with some non-zero probability into the CCDIS channel 92. Nuance makes the distinction between resonant and non-resonant background within a single channel but the experimentalist is not

[9] The full list is available in the `Nuance_defaults.cards` file. A list showing the most relevant channels can be found in the "Rates" section.

afforded this luxury.

GENIE cuts off resonant interactions above 1.7 GeV and uses:

W_{high}(= 1.7 GeV by default)

$$\frac{d^2\sigma}{dWdQ^2}_{DIS} = \frac{d^2\sigma}{dWdQ^2}_{BY} \sum_m R_m * P_m^{had} \quad \text{if} \quad W < W_{high}$$

$$\frac{d^2\sigma}{dWdQ^2}_{DIS} = \frac{d^2\sigma}{dWdQ^2}_{BY} \quad \text{if} \quad W > W_{high}$$

where R_m is a tunable parameter and P_m^{had} is the hadronization model probability that the DIS final state multiplicity is equal to m. The R_m factors are very much data-driven and are tuned to give agreement between the total cross section and the world's 1-pion and 2-pion cross section data [2]. The numerical values of the 16 [one per channel, corresponding to $2(\nu/\overline{\nu})\times 2$(hit neutron/proton)$\times$2(CC/NC)$\times$2(1 pion/2 pion final state)=16] free R_m parameters can be found in the GENIE documentation [2]. Note that W refers to the invariant mass selected by GENIE during event generation. This means that it is computed with complete event kinematic information including Fermi momentum. There is another "smeared W" that neglects the unobservable Fermi momentum and can go above 1.7 GeV.

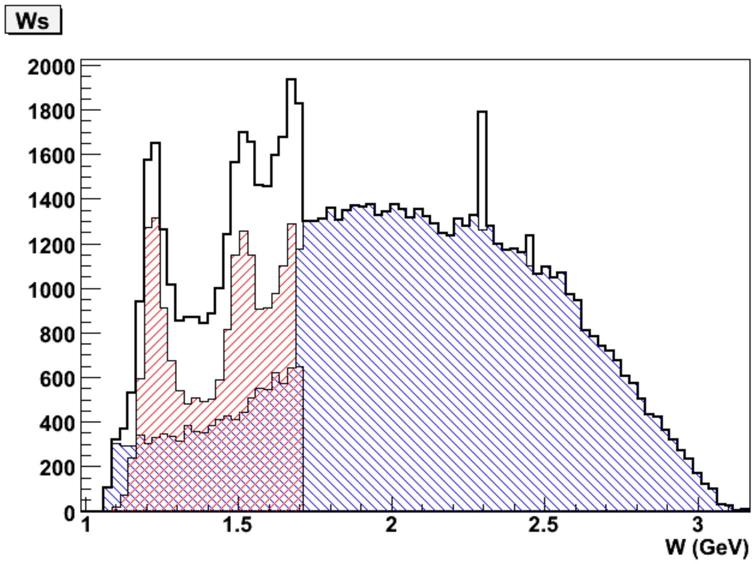

Figure 18: Invariant mass (W) of 5 GeV neutrino-neutron interaction in GENIE showing the resonance region and above. The red area is resonant, the blue area is DIS. The ambiguous "resonant/DIS" below W=1.7 GeV is sometimes referred to as non-resonance inelastic background in the resonance region [47].

A hard cut or parametrization type for the transition region and definition of DIS will need to be chosen. The advantages and disadvantages of each parametrization/definition as well as the experimentalist's responsibility to maintain "smoothness" in the transition region are unclear to the author.

8 Parameters

The table below shows some important parameters that go into neutrino event generation in LAr. The parameters have been made to match in Nuance and GENIE (with a strong preference towards GENIE's more up-to-date values). The LAr-specific Woods-Saxon parameters have been taken from [48]. A full list of all the parameters and specific models used can be found in ANT_GENIE/GENIE_LAr_source/config/UserPhysicsOptions.xml and ANT_Nuance/Nuance_defaults.cards. A subjective attempt to maintain generator integrity has been made and of course, not all parameters/models are reconciled.

LAr	Nucleon binding energy= 29.5 MeV Fermi Momentum (p)= 242 MeV Fermi Momentum (n)= 259 MeV Density=1.396 g/cm^3
LAr nuclear density $\rho(r) = \frac{\rho_0}{1+e^{(r-c)/z1}}$	c=3.53 fm z1=.542 fm
CCQE	M_A=.990 GeV M_V=.840 GeV $F_A(Q^2 = 0)$=-1.2670
NCelastic	M_A=.990 GeV M_V=.840 GeV
Single pion resonant	M_A=1.120 GeV M_V=.840 GeV Ω_{FKR}=1.05
Coherent	M_A=1.00 GeV

9 Conclusion

An overview of Nuance and GENIE for LAr has been presented. This work has described GENIE and Nuance code changes for LAr, cross sections, nuclear effects, and the transition region for relevant ArgoNeuT (and future LAr experiment) processes. As neutrino data becomes available in ArgoNeuT and a cross section measurement becomes possible, the generators will need to be revisited and a closer look be taken. That being said, this document and corresponding code provide a backbone for a Monte Carlo truth-to-data comparison in ArgoNeuT and a starting point for future liquid argon experiments.

9.1 A word on GENIE "versus" Nuance

GENIE is fully supported and updated on a regular basis. Nuance is not supported and has not been updated since 2004. Along with new nuclear process parametrizations, cross section data and models, and PDG values since then, Nuance does not include such important processes as anomaly-mediated gamma [49] and pion re-interactions to produce new resonances. Such processes will be vital in understanding the MiniBooNE low-energy excess with MicroBooNE. GENIE simulates all of the above (with anomaly-mediated gammas to 0-th order). Although MiniBooNE has added or is in the process of adding all of the aforementioned processes to Nuance, the code is not publicly available. Even if acquired, the updated Nuance code will quickly become obsolete and it may not be worth updating the Nuance code further with an up-to-date GENIE already in hand. It is not worth disregarding Nuance entirely, however. As has been shown, Nuance provides a wonderful comparison and sanity check tool to GENIE. Nuance's treatment of the transition region, definition of DIS, neutrino channel organization, intra-nuclear model, etc. have been and will continue to be valuable in optimizing and validating GENIE. Furthermore, Nuance and event generator discussion in general is readily available to ArgoNeuT collaborators given the close ties and collaboration overlap between neutrino experiments such as MiniBooNE at FermiLab.

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